

# **Level Densities Far from Stability**

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## Motivation for Study of Level Density Off the Line of Stability

- Is there an enhancement at  $N=Z$ ? Is there an isospin dependence?
- What happens as you approach the drip lines?
- Hartree calculations on stable and unstable nuclei indicate there may be something interesting as you approach the driplines.
- Calculations in light nuclei showed that the convergence to equal positive and negative parity states can be up to several MeV.

## Bethe Formalism for Level and State Densities

$$\rho(u) = \frac{\sqrt{\pi} \exp 2\sqrt{au}}{12 a^{1/4} u^{5/4}} \quad (1)$$

$$\rho_L(u) = \frac{1}{\sqrt{2\pi}} \frac{1}{\sigma} \rho(u) \quad (2)$$

$\rho$  is the state density

$a$  is the level density parameter

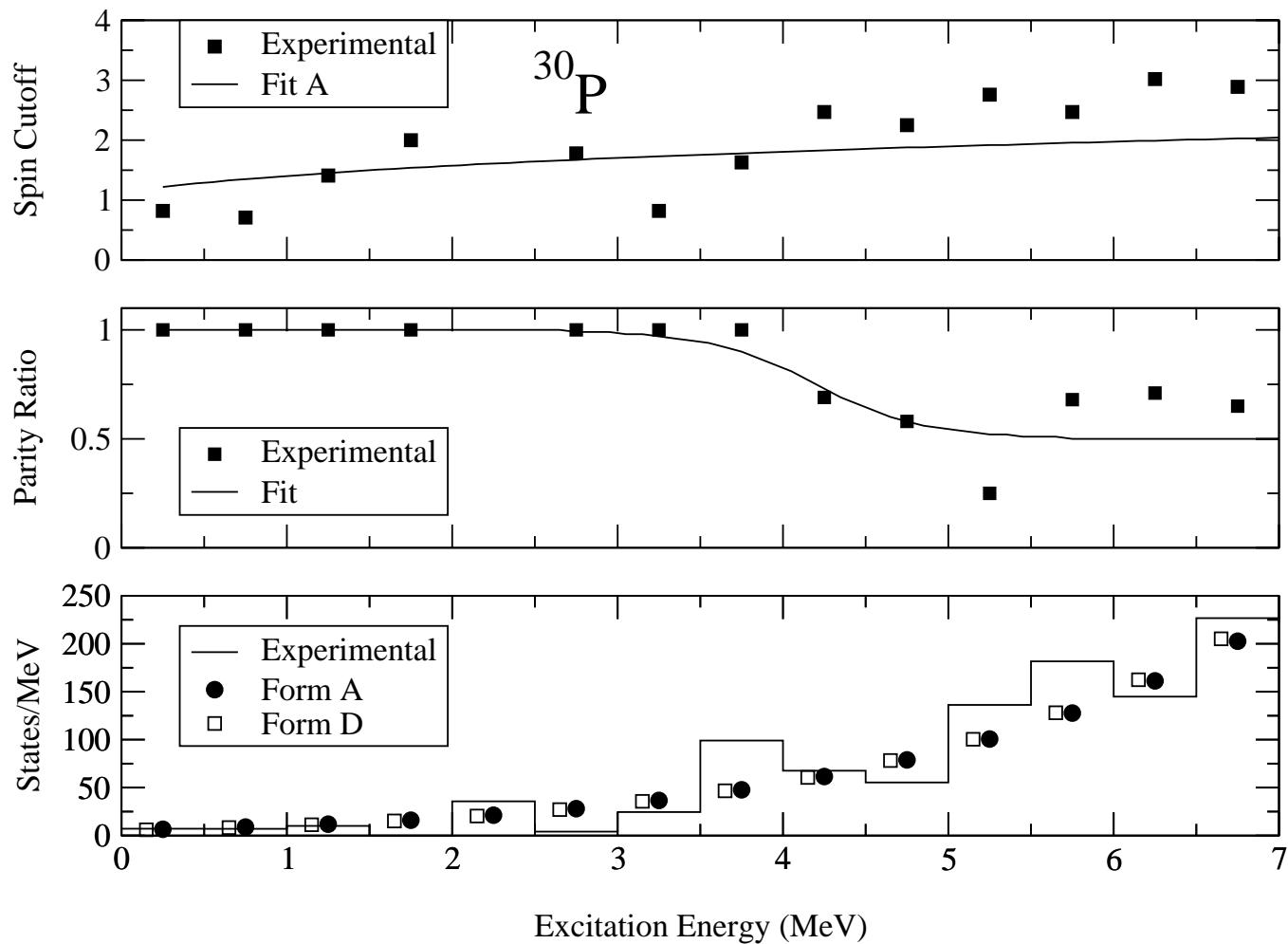
$u$  is the reduced energy,  $E_x - \delta$

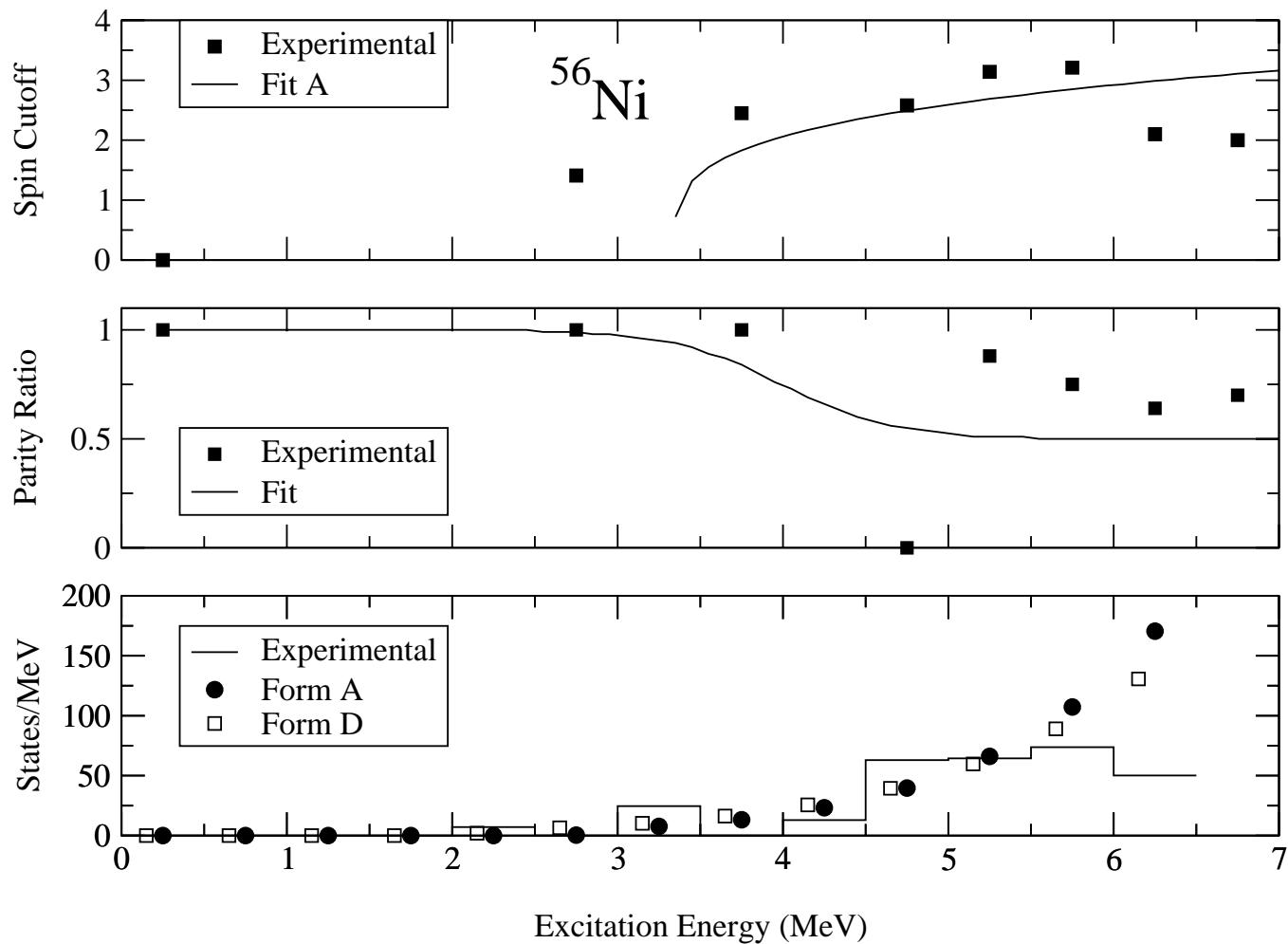
$\rho_L(u)$  is the level density

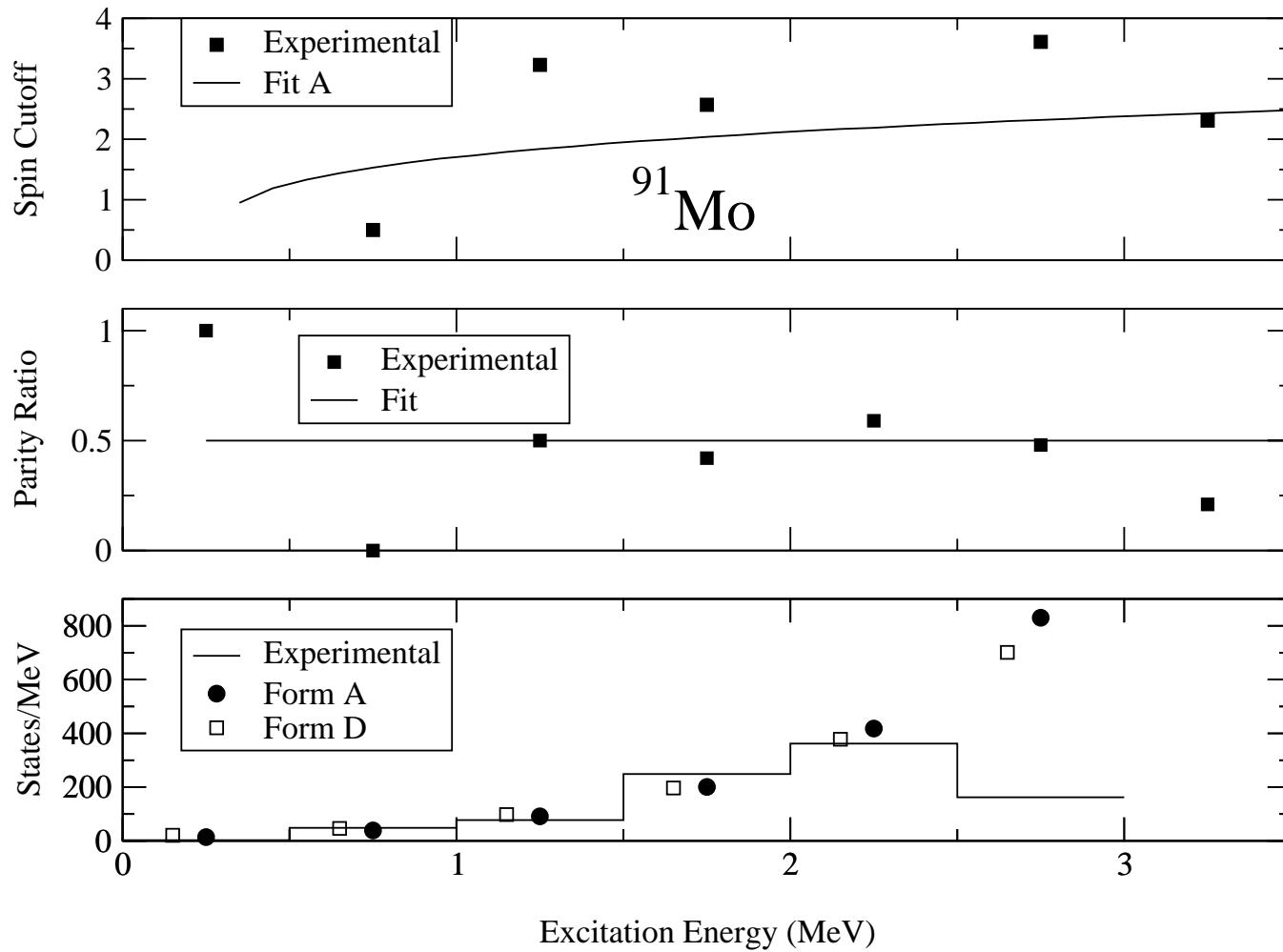
$\sigma$  is the spin cutoff parameter

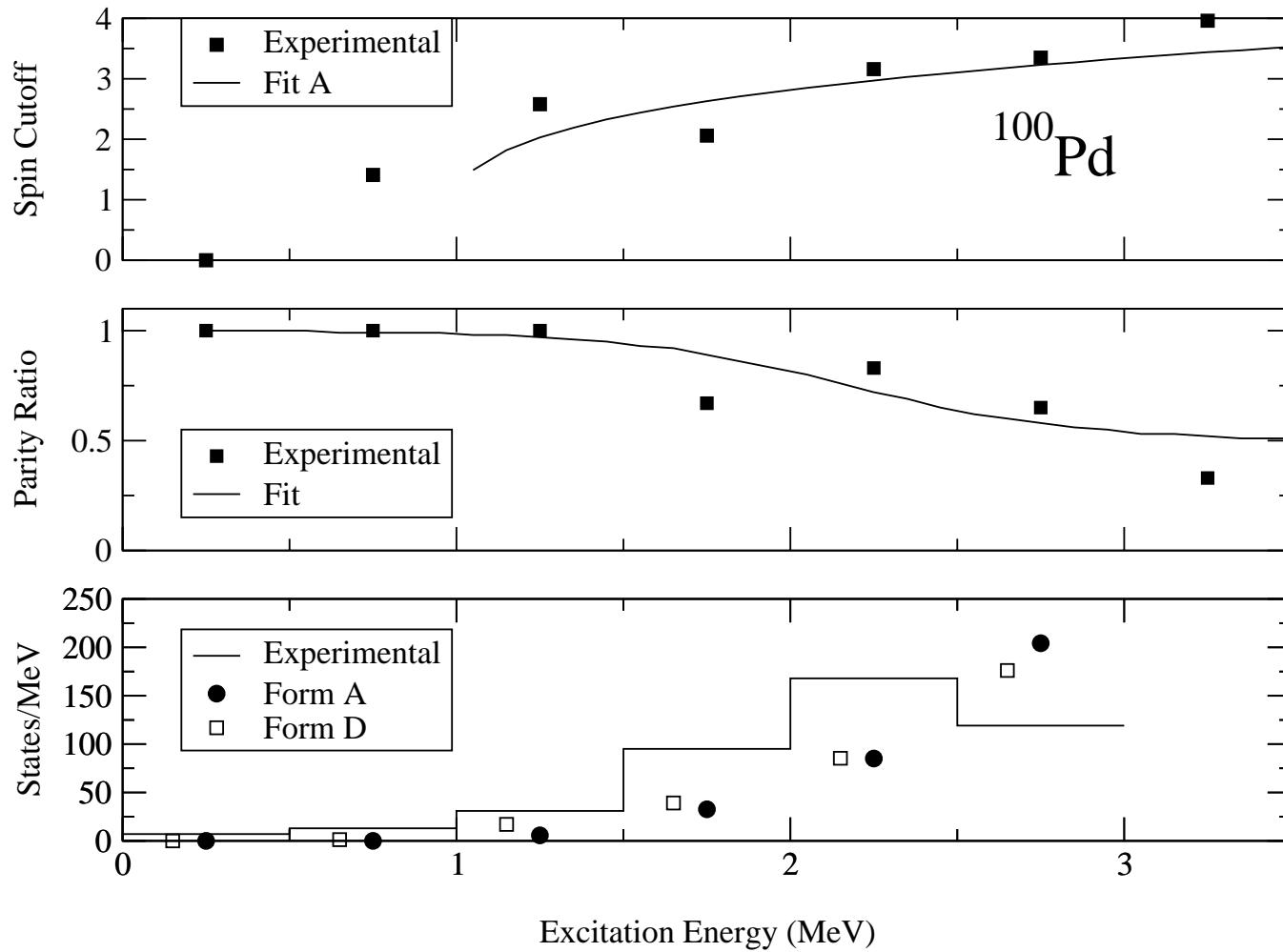
## Methodology for Study Using Known Levels

- All tabulated levels in ENSDF were used from  $A=20 - 100$ . All Sn isotopes and  $A=140$  isotopes were also used.
- The state density was compared to calculation to determine how high in energy the levels were complete.
- The delta for each nucleus was determined and the parameterization of the level density parameter was varied to obtain the best fit.
- The spin cutoff and parity ratio were determined from the "good" data set.









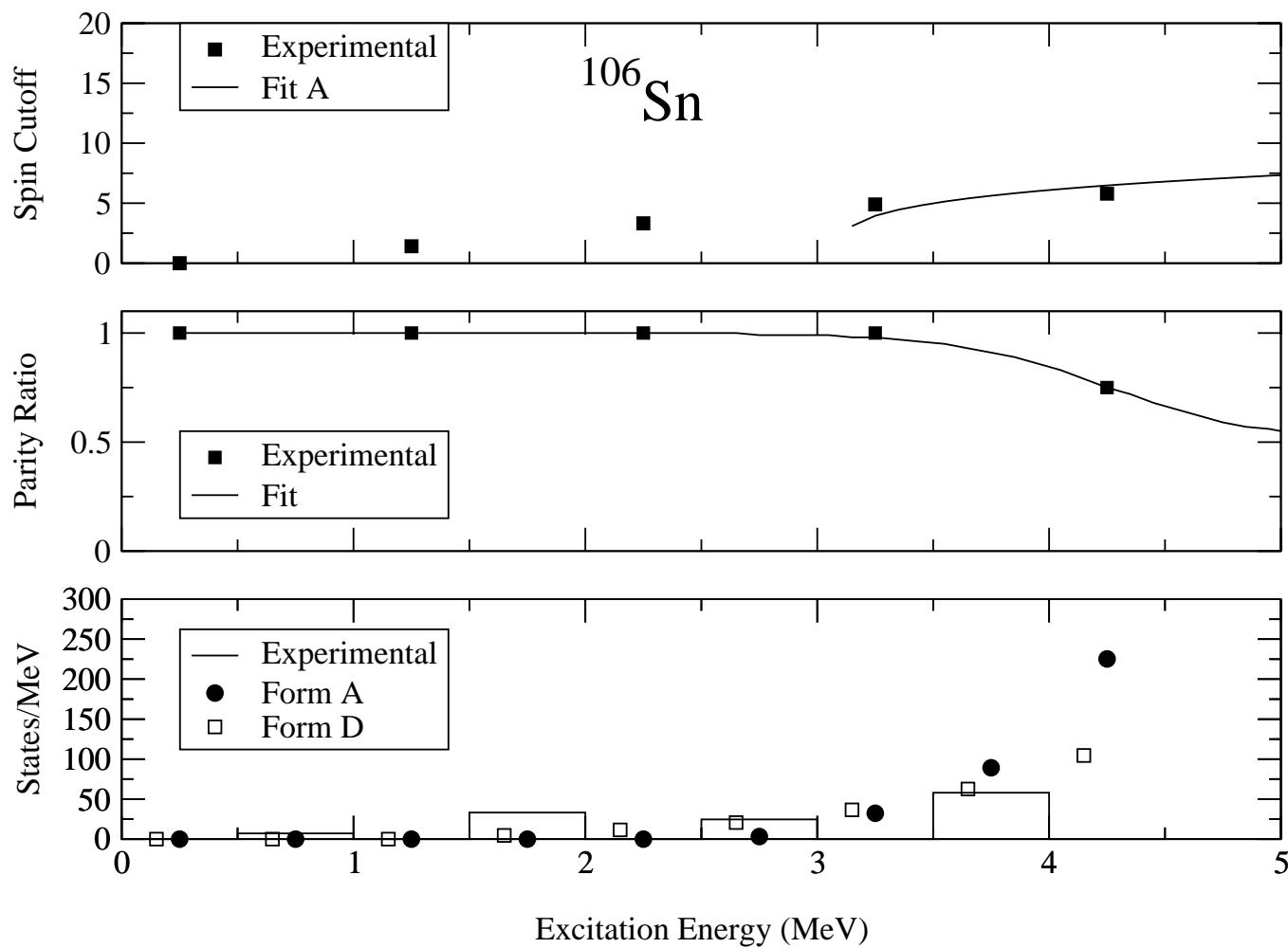


Table 1: Forms for the dependence of  $a$  on various parameters

	Form	Parameter Values	$\chi^2$ Relative to Eq. (3)
(A)	$\alpha A$	$\alpha = 0.1016$	1
(B)	$\alpha A + \beta A^{2/3}$	$\alpha = 0.0481;$ $\beta = 0.2037$	0.933
(C)	$\alpha A \exp[\beta(N - Z)^2]$	$\alpha = 0.1062;$ $\beta = -0.00051$	0.916
(D)	$\alpha A \exp[\gamma(Z - Z_0)^2]$	$\alpha = 0.1068;$ $\gamma = -0.0389$ $Z_0 = 0.5042A/(1 + 0.0073A^{2/3})$	0.891
(E)	$\alpha A \exp[\beta(N - Z)^2 + \gamma(Z - Z_0)^2]$	$\alpha = 0.1073;$ $\beta = -0.00022$ $\gamma = -0.0289$ $Z_0 = 0.5042A/(1 + 0.0073A^{2/3})$	0.881
(F)	$\alpha A \exp[(\beta(N - Z)^2 + 1)\gamma(Z - Z_0)^2]$	$\alpha = 0.1076;$ $\beta = -0.00084;$ $\gamma = -0.0527$ $Z_0 = 0.5042A/(1 + 0.0073A^{2/3})$	0.881

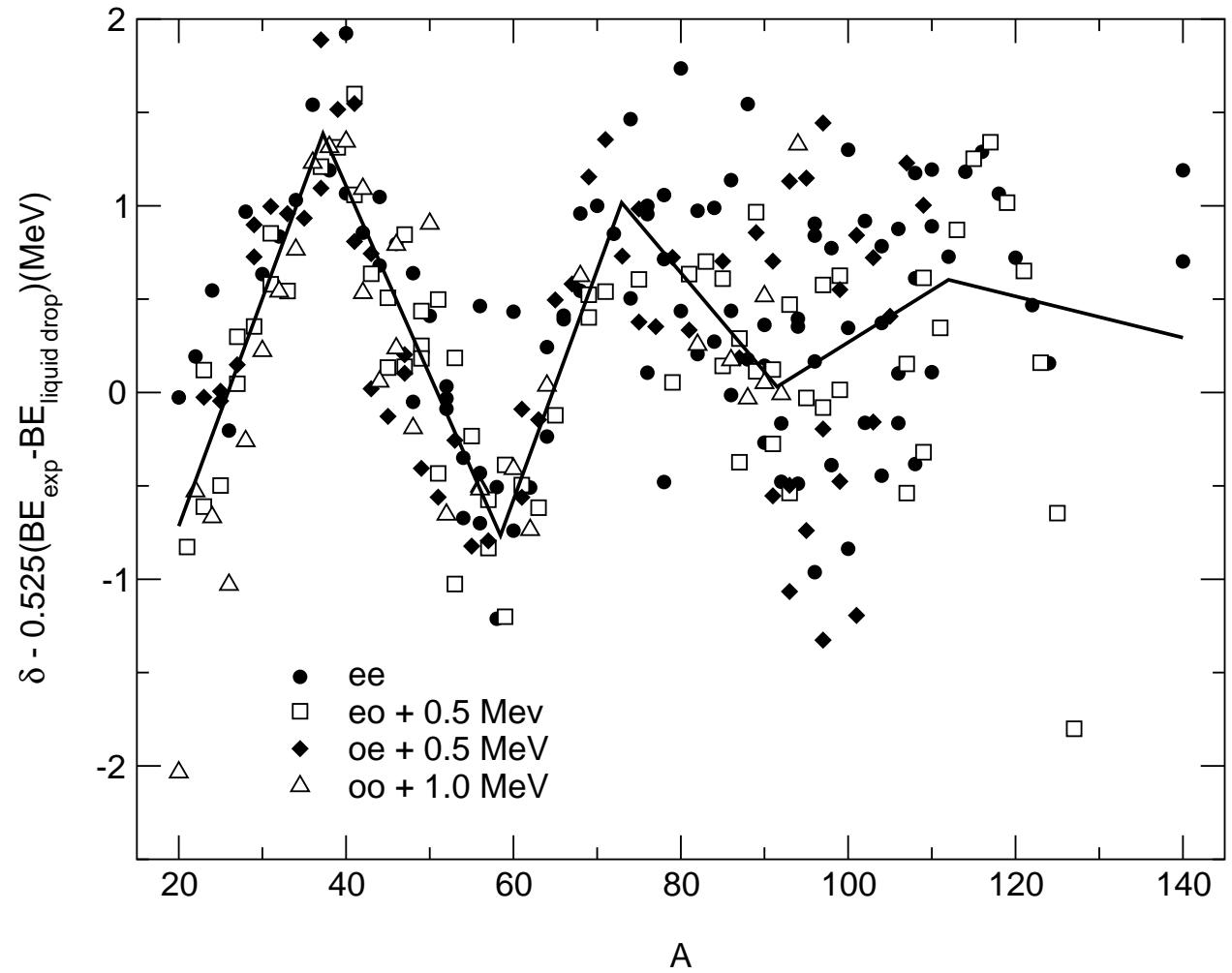


Table 2: Mass Formula Parameters

$$\begin{aligned}
 M(Z, N) = & Z_{mp} + N_{mn} - a_v A + a_s A^{2/3} \\
 & + (a_{co} - a_{ci}/A^{1/3}) Z^2/A^{1/3} \\
 & + a_a (Z)^2/A
 \end{aligned}$$

$$a_v = 14.769$$

$$a_s = 15.780$$

$$a_{co} = 0.6909$$

$$a_{ci} = 0.4469$$

$$a_a = 19.22$$

## Parameterization of the Parity Ratio

Definition of parity ratio:

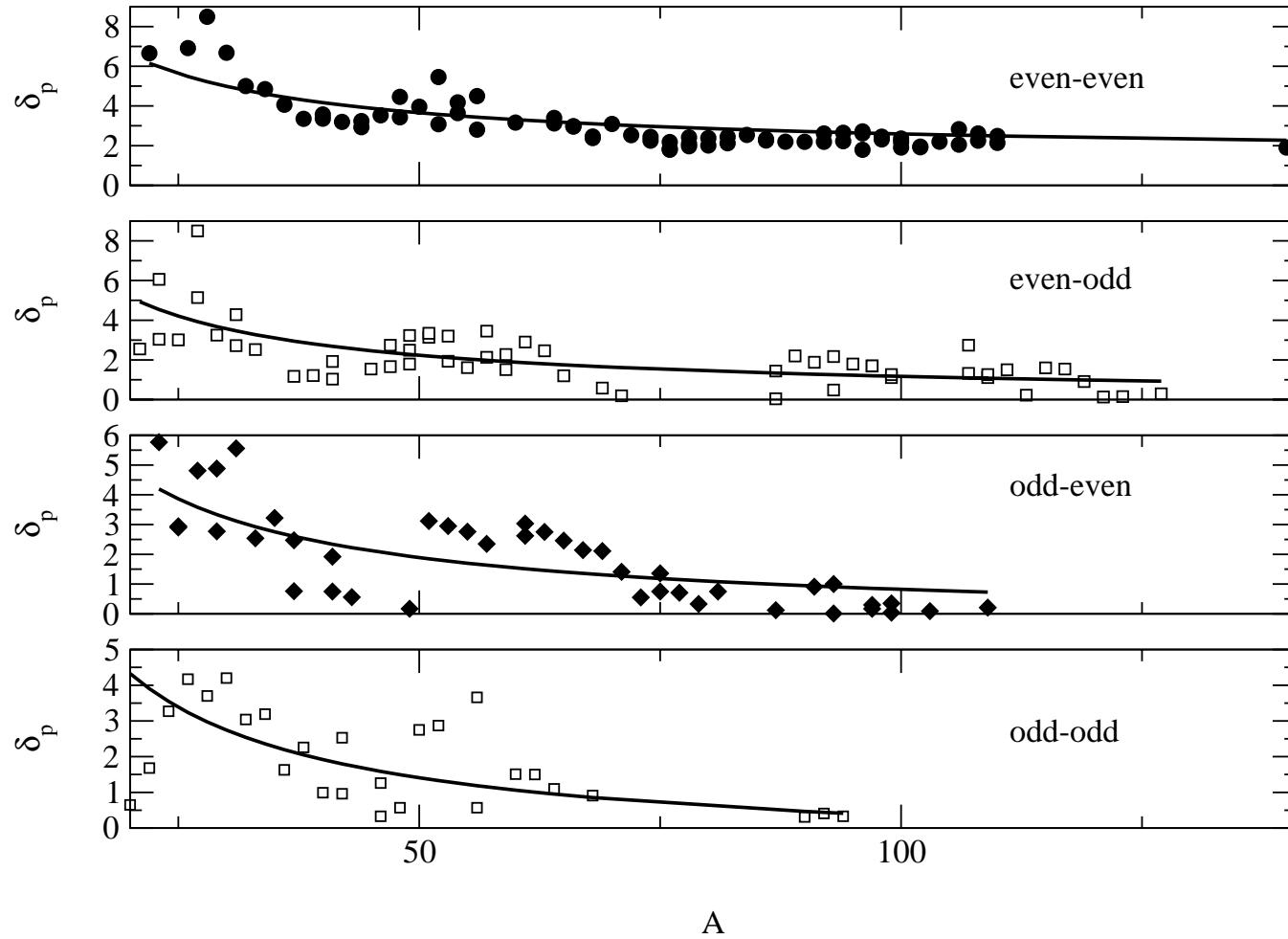
$$\pi(u) = \frac{\rho_+(u)}{(\rho_+(u) + \rho_-(u))} \quad (3)$$

where  $\rho_+(u)$  is the positive parity state density and  $\rho_-(u)$  is the negative parity state density.

The parity ratio was then fit to the form:

$$\pi(u) = \frac{1}{2} \left( 1 \pm \frac{1}{1 + \exp C(u - \delta_p)} \right) \quad (4)$$

where + was used for nuclei for which  $\pi(u)$  approached 1 at low  $u$  and - was used for those which approached 0. Good fits were obtained by fixing  $C$  at  $3 \text{ MeV}^{-1}$  and allowing the shift  $\delta_p$  to vary.



The spin cutoff parameter,  $\sigma$ , is defined by the equations:

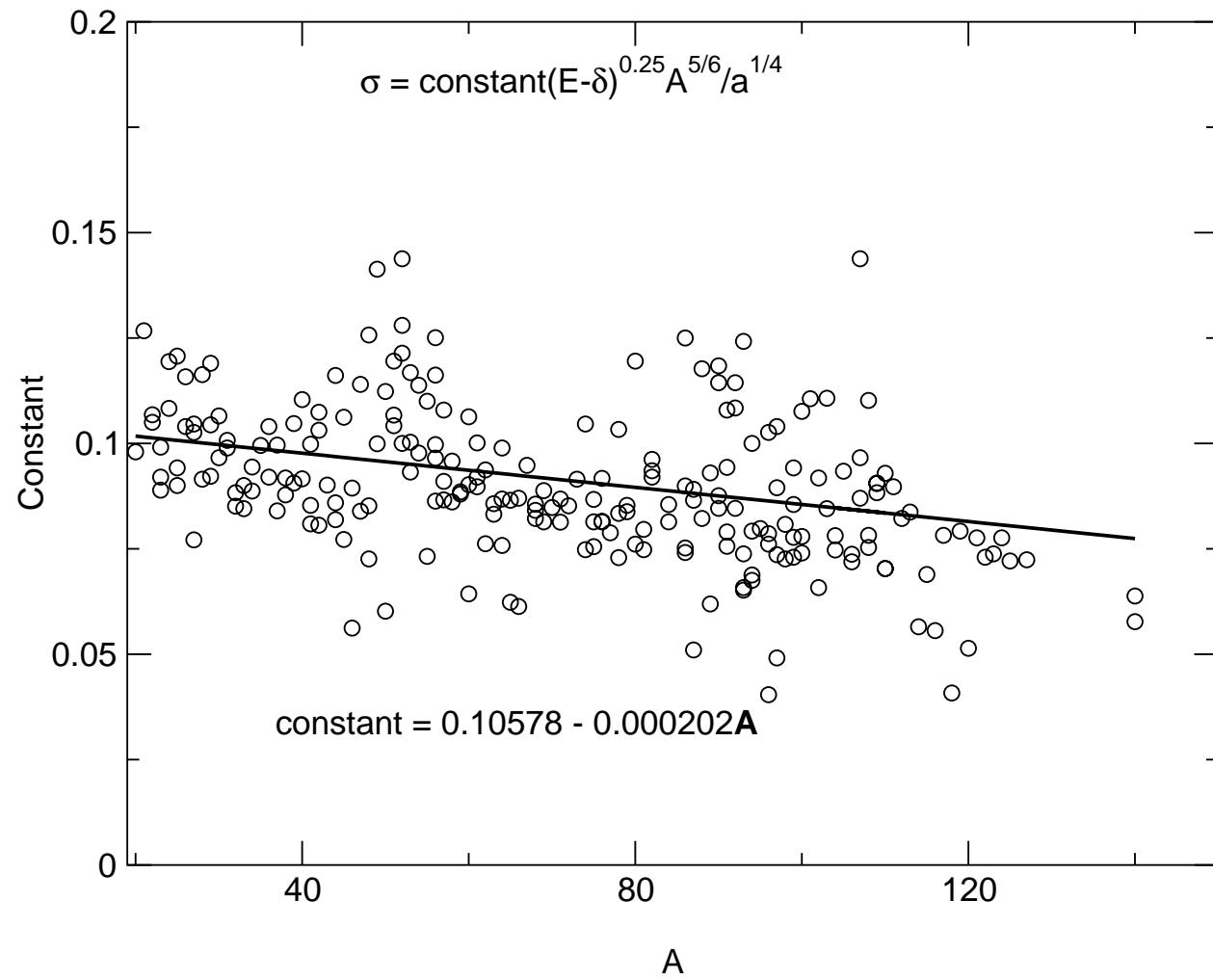
$$\sigma = \langle J_z^2 \rangle^{1/2} = \sqrt{\frac{1}{3} \langle J(J+1) \rangle} \quad (5)$$

$$\sigma(U) = \left( \frac{\sum_J J(J+1)\rho(U,J)}{\sum_J 3\rho(U,J)} \right)^{\frac{1}{2}} \quad (6)$$

The two common formulas for parameterizing the spin cutoff parameter are:

$$\sigma^2 = 0.0145 A^{5/3} \sqrt{\frac{u - \Delta}{a}} \quad [\text{rigid body}] \quad (7)$$

$$\sigma^2 = 0.1461 \sqrt{a(u - \delta)} A^{2/3} \quad [\text{statistical mechanical}] \quad (8)$$



## Hauser – Feshbach Code HF2002

- Five (5) step evaporation allowed.
- Angular distributions for the first stage only.
- Isospin used as good quantum number.
- Isospin mixing explicitly defined.
- Rohr, Huang I and II, Al-Quraishi I and II parameters included as options, energy dependent parity ratio, standard energy dependence for spin cutoff.
- All incoming projectiles handled, Outgoing particles  $\gamma$ , n, p, d, t,  $^3He$ , and  $\alpha$  in addition to the incident particle.
- A preequilibrium package is planned to be added eventually.

## Current Techniques for Looking for Z dependence

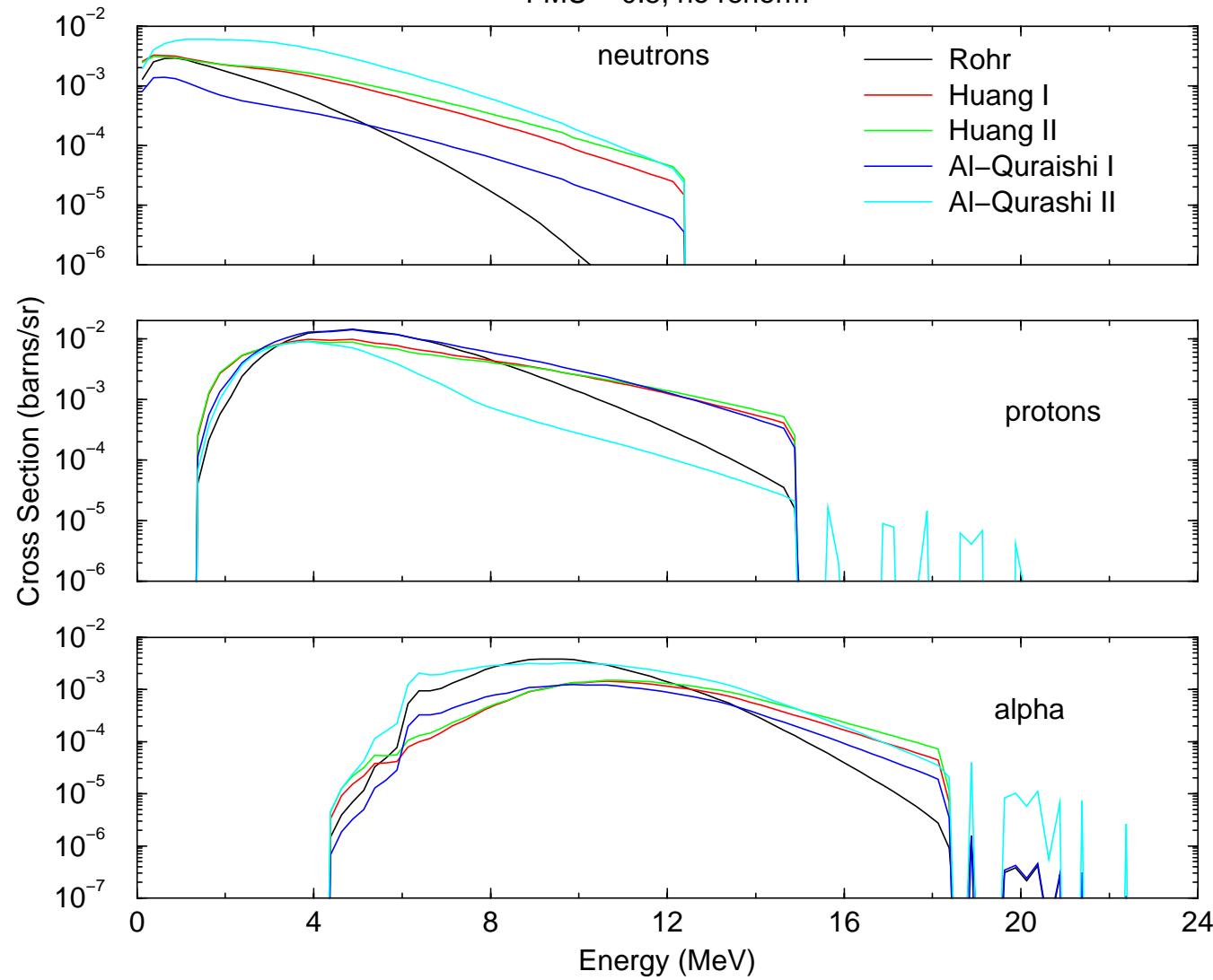
- Precision measurement of nuclear level densities near line of stability.
- Choice measurement with light ions to get off the line of stability, for example using the  $(^3He, n)$  and  $(^7Li, p)$  reactions at energies where compound reactions dominate.
- Measurements using natural abundance samples with gamma-ray, and neutron or charged particle coincidence..

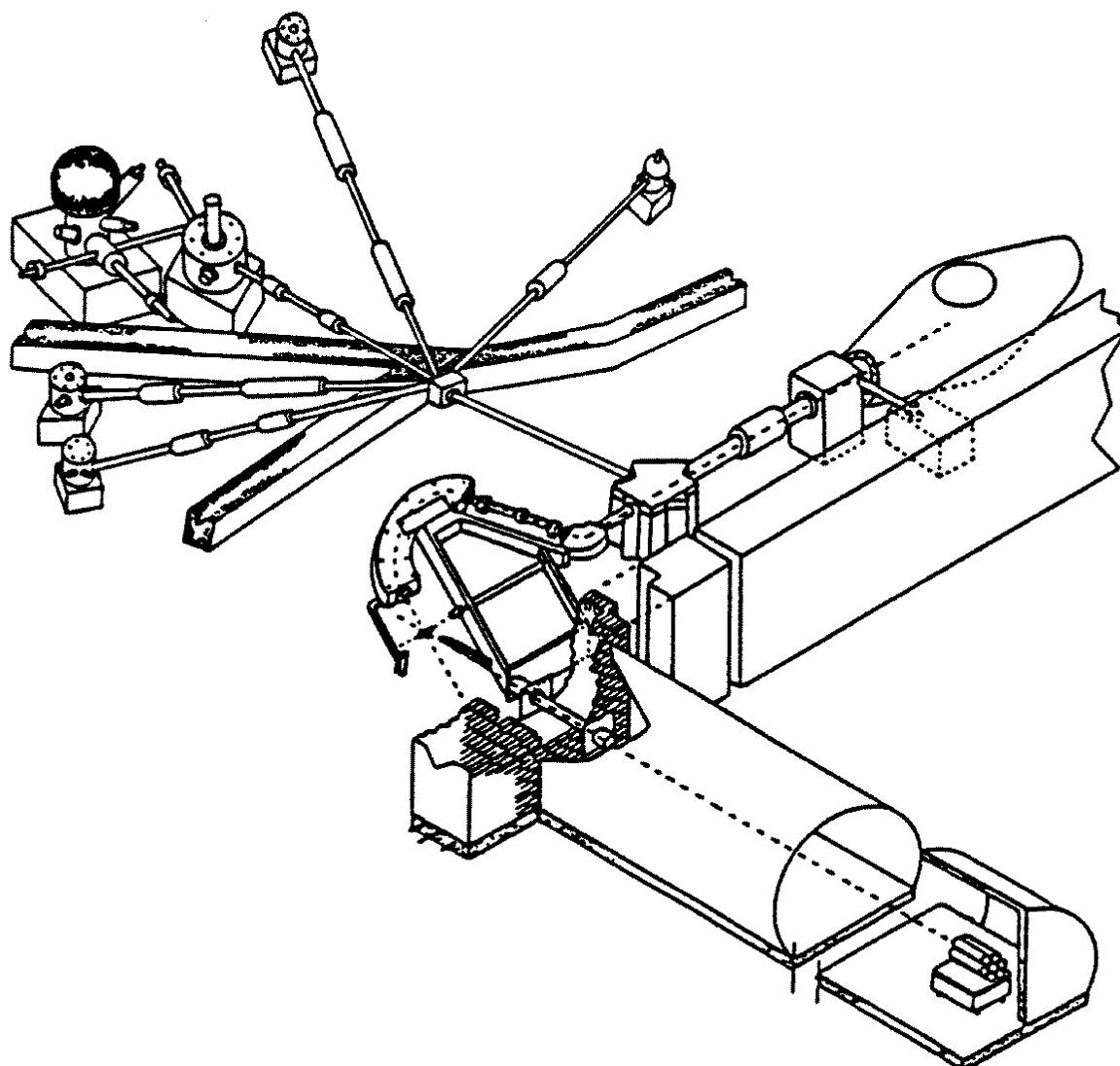
## Future Methods for Looking for Z dependence

- Heavy ion reactions with the incident energy chosen to maximize the sensitivity to the Z dependence of the level densities. Proposed experiment of Nickel isotopes bombarded with carbon at Hahn Meitner Institute.
- Radioactive ion beam incident on a carbon target. This should be a clean way to explore off the line of stability. An experiment has been proposed at Oakridge.
- Incident particles heavier than deuterons transfer sufficient angular momentum that the spin cutoff parameter may be extracted from the anisotropy, in addition to the level densities.

$^{12}\text{C} + ^{58}\text{Ni}$  30 MeV

FMU = 0.5, no renorm

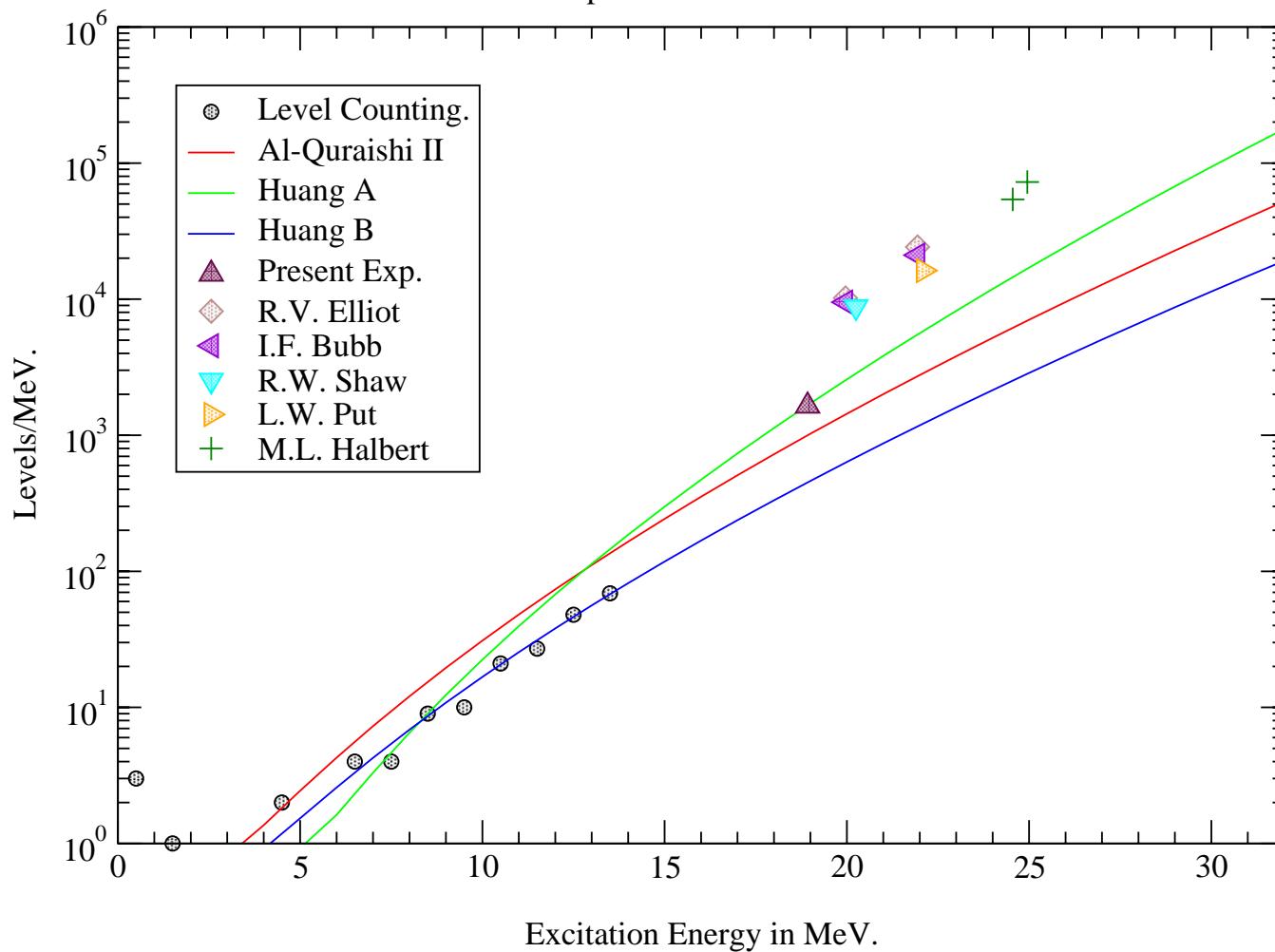




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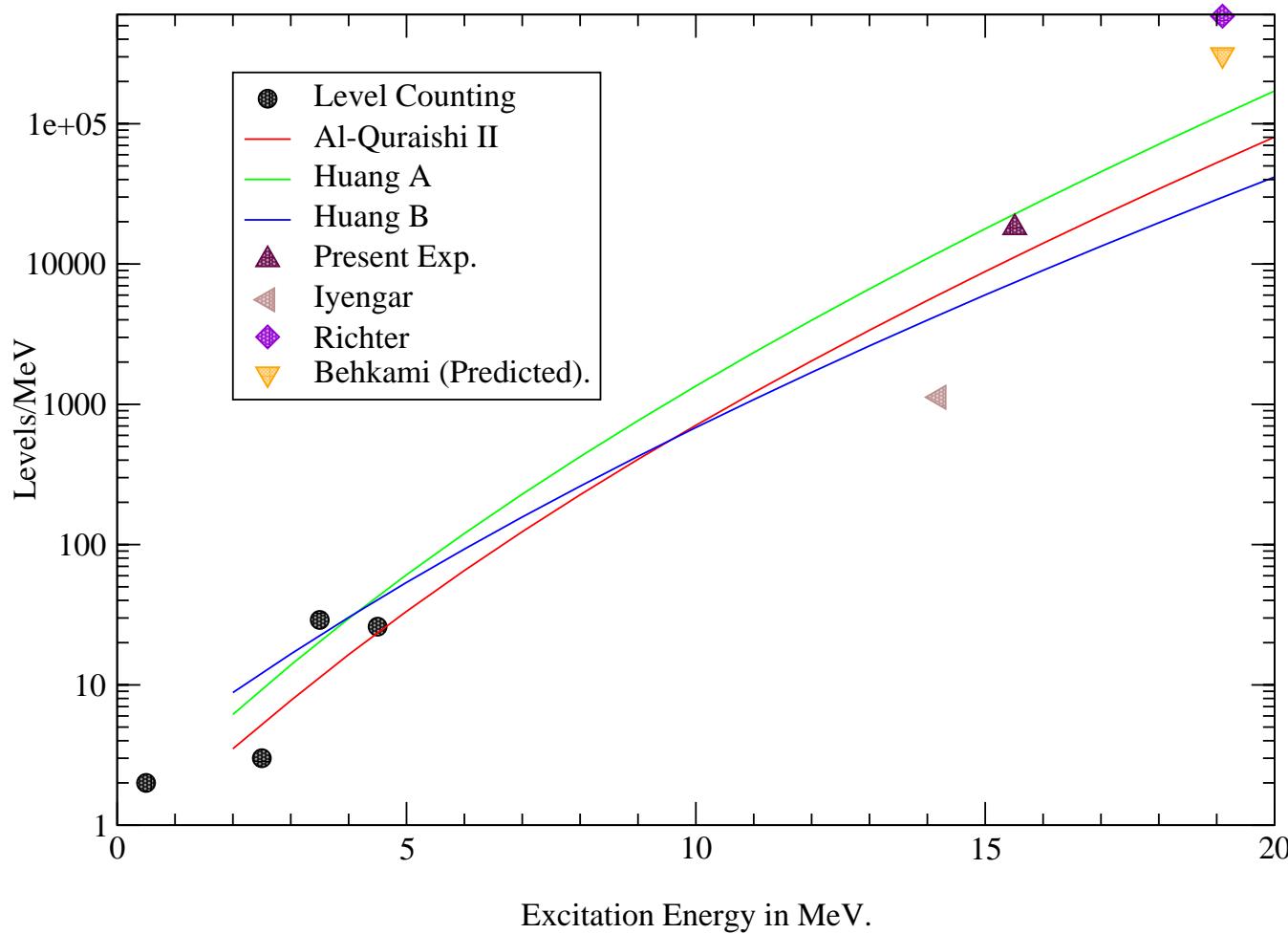
## Level Counting and Level Density for Si-28.

spin cutoff : 1.5983



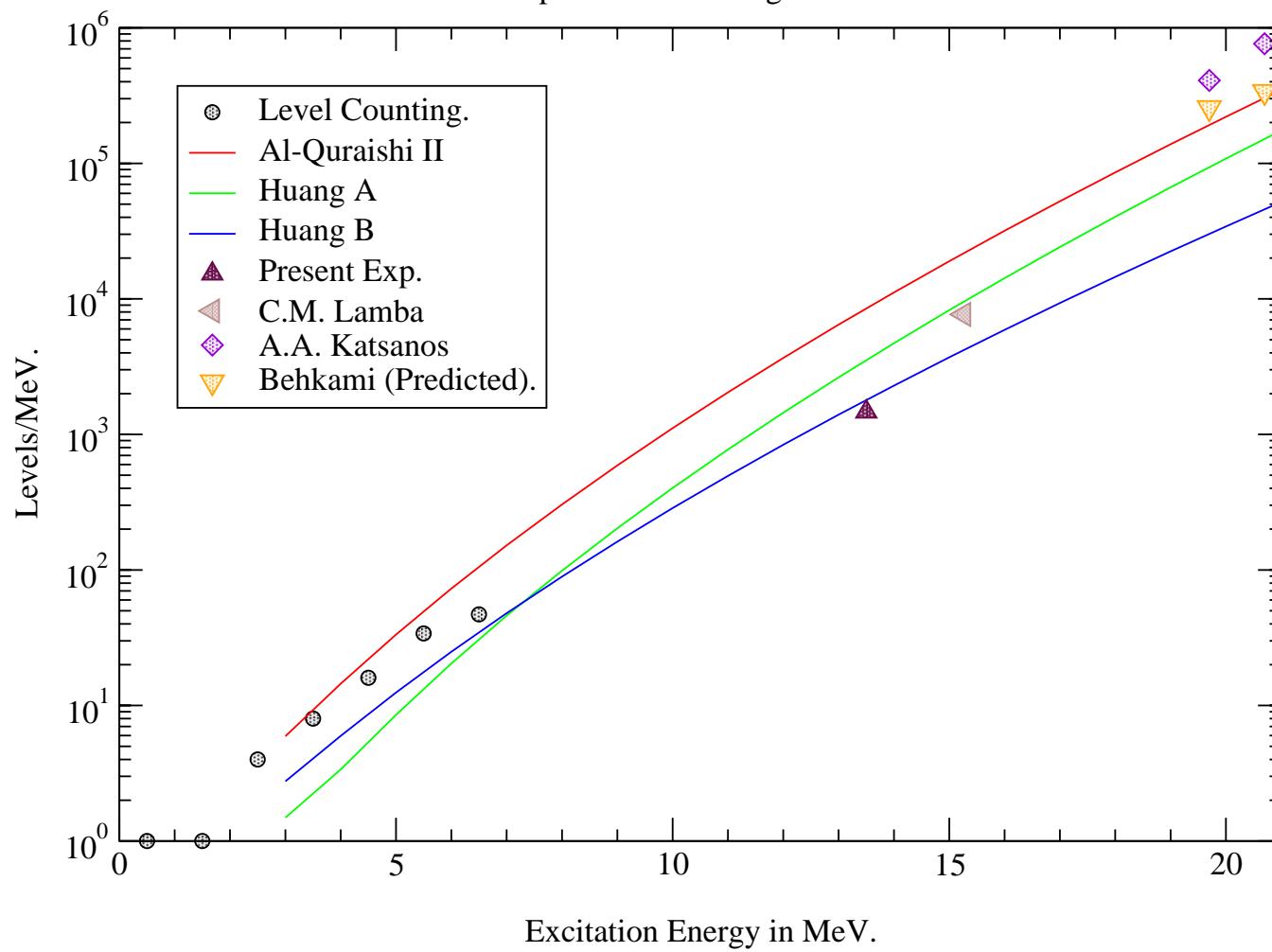
# Level Counting and Level Density for $^{46}\text{Ti}$

Spin Cutoff: Solid Rigid, LDP: Po Lin A.



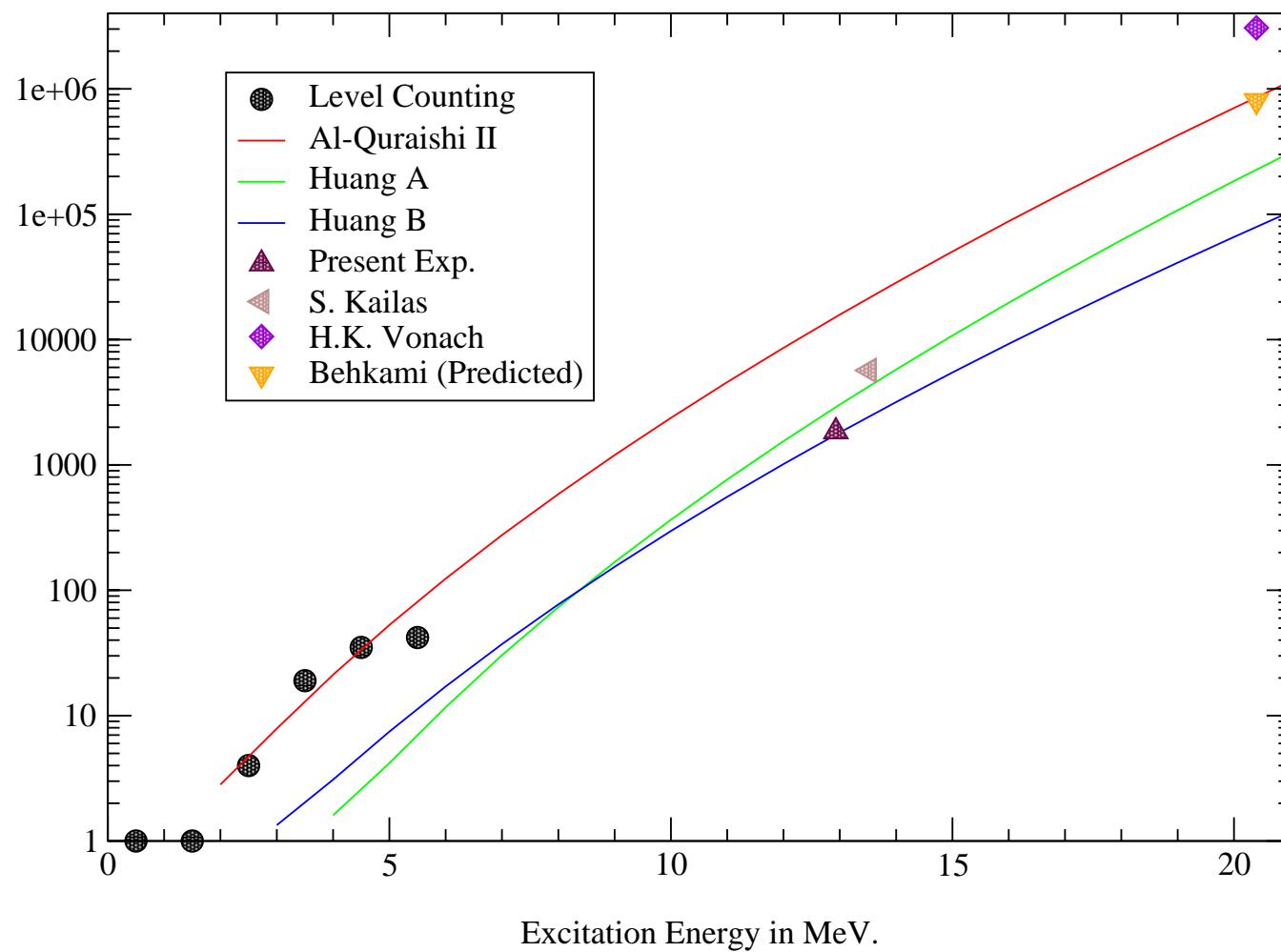
## Level Counting and Level Density for Cr-52.

spin cutoff solid rigid =4.4



# Level Counting and Level Density for $^{60}\text{Ni}$

Spin Cutoff: Solid Rigid.



## Level Counting and Level Density for $^{28}\text{Si}$

Spin Cutoff=3.0 (solid rigid)

